Sediment Deposition in the White River Reservoir, Northwestern Wisconsin

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CONVERSION FACTORS

For those who prefer to use metric units rather than inch-pound units, the conversion factors for terms used in this report are listed below.

Multiply inch-pound unit	*By*	*To obtain SI (metric) unit*
mi (mile)	1.609	km (kilometer)
ft (foot)	3.048×10^{-1}	m (meter)
in. (inch)	2.54×10^{1}	mm (millimeter)
mi^2 (square mile)	2.590	km^2 (square kilometer)
acre	4.047×10^{-1}	ha (hectare)
acre–foot (acre–ft)	1.233×10^{3}	m^3 (cubic meter)
ft^3 /s (cubic foot per second)	2.832×10^{-2}	m^3/s (cubic meter per second)
ton/mi^2 (ton per square mile)	3.503×10^{-1}	t/km^2 (metric ton per square kilometer)
lb (pound)	4.535×10^{-1}	kg (kilogram)
lb/ft^3 (pound per cubic foot)	1.602×10^{-2}	g/cm^3 (gram per cubic centimeter)

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By W. G. BATTEN and S. M. HINDALL

ABSTRACT

The history of deposition in the White River Reservoir was reconstructed from a study of sediment in the reservoir. Suspended-sediment concentrations, particle size, and streamflow characteristics were measured at gaging stations upstream and downstream from the reservoir from November 1975 through September 1977. Characteristics of the sediments were determined from borings and samples taken while the reservoir was drained in September 1976. The sediment surface and the prereservoir topography were mapped. Sediment thickness ranged from less than 1 foot near the shore to more than 20 feet in the old stream channel.

The original reservoir capacity and the volume of deposited sediment were calculated to be 815 acre-feet and 487 acre-feet, respectively.

Sediment size ranged from clay and silt in the pool area to large cobbles and boulders at the upstream end of the reservoir. Analyses of all samples averaged 43 percent sand, 40 percent silt, and 17 percent clay, and particle size typically increased upstream. Cobbles, boulders, and gravel deposits were not sampled. The average density of the deposited sediment was about 80 pounds per cubic foot for the entire reservoir.

The reservoir was able to trap about 80 percent of the sediment entering from upstream, early in its history. This trap efficiency has declined as the reservoir filled with sediment. Today (1976), it traps only sand and silt-sized sediment, or only about 20 percent of the sediment entering from upstream. Data collected during this study indicate that essentially all of the clay-sized sediment (<0.062 mm) passes through the reservoir.

The gross rate of deposition was 7.0 acre-feet per year over the reservoir history, 1907–76. Rates during 1907–63 and 1963–76 were 7.4 and 5.7 acre-feet per year, respectively, determined by the cesium-137 method.

Based on scant data, the average annual sediment yield of the total 279 square mile drainage area above the gaging station at the powerhouse was about 50 tons per square mile. Analysis of the drainage-basin characteristics indicates that most of this sediment was derived from less than 10 percent of the total drainage area and from steep unvegetated streambanks.

INTRODUCTION

Erosion of the red clay in northwestern Wisconsin and deposition in Lake Superior has received considerable attention in recent years. This highly erodible clay covers a scenic 1,400 mi^2 lowland area bordering Lake Superior. Natural erosion is rapid, particularly along streambanks and the shore of Lake Superior, and is aggravated where improper land use has left the clay unprotected by vegetation.

Comparisons of sediment yields with those in other areas in Wisconsin illustrate the problem. Only two areas, the heavily farmed steep-sloped "Driftless Area" of southwestern Wisconsin having sediment yields commonly in excess of 500 $tons/mi^2/yr$ and small areas of expanding urbanization in the southeastern part of the State, have sediment yields as high or higher than the red-clay area. For comparison, a yield of 480 $(tons/mi^2)/yr$ was obtained for one drainage area covered by red-clay soils. The average sediment yield for Wisconsin is only 80 $(tons/mi^2)/yr$ (Hindall, 1976).

Knowledge of the past rates of erosion in the red-clay area of northwestern Wisconsin is essential to understand the magnitude of the present erosion problem. The White River Reservoir, having 69 years of filling, provides an excellent opportunity to study the sedimentation rate. This sedimentation rate can be used to evaluate the potential of small headwater reservoirs in reducing red-clay loads of streams.

PURPOSE AND SCOPE

The purpose of this report is to describe sediment deposition in the White River Reservoir in terms of rates, amounts, type, and characteristics of deposited material.

Geologic, hydrologic, sediment, and chemical-quality data for the project were collected from May 1976 through December 1976. Major emphasis of the study dealt with sedimentation in the White River Reservoir as a guide to past erosion rates in the red-clay area of northwestern Wisconsin.

LOCATION

The White River Reservoir is in Ashland County in northwestern Wisconsin, 6 mi south of Ashland (fig. 1). The drainage area of the White River above the reservoir is almost completely in Bayfield County.

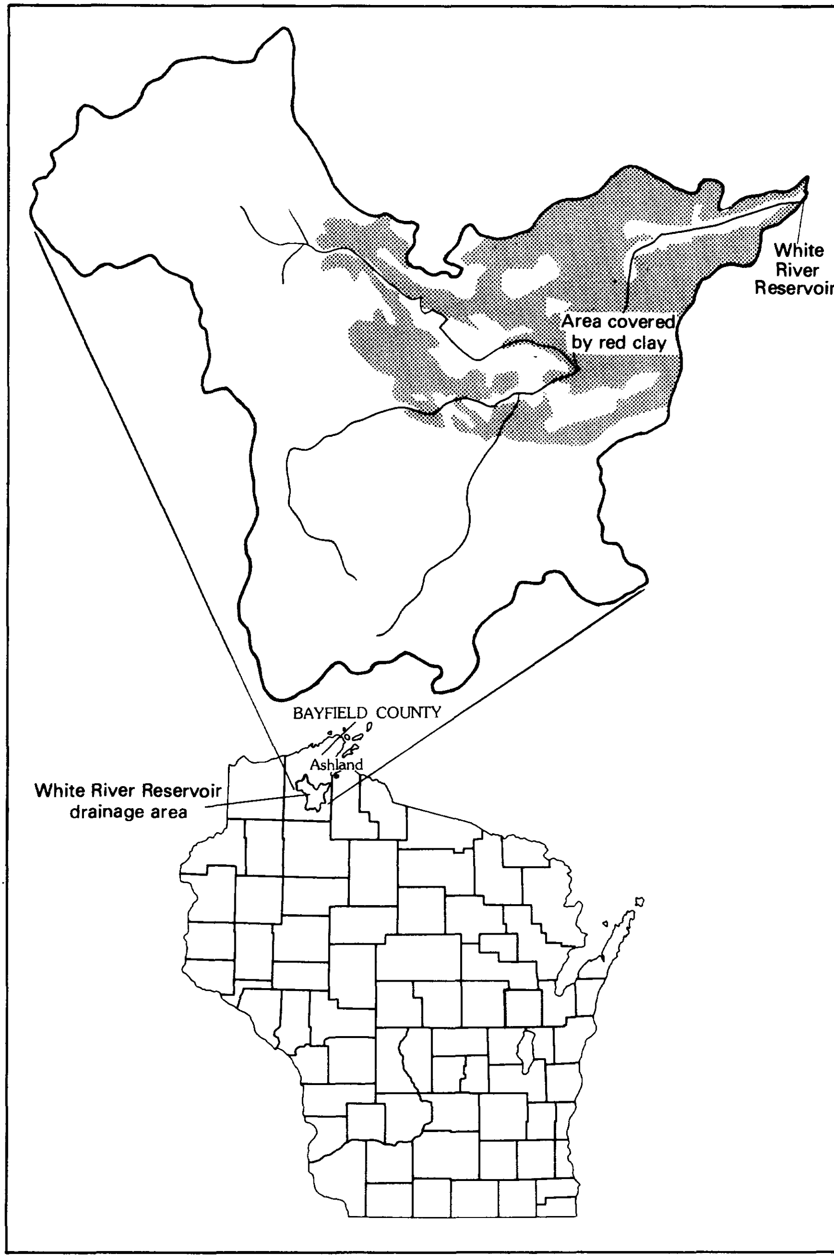

FIGURE 1.—Location of the White River Reservoir and its drainage area.

ACKNOWLEDGMENTS

This study was made by the U.S. Geological Survey in cooperation with the Wisconsin Department of Natural Resources.

Special acknowledgment is given to the Lake Superior District Power Company for allowing reservoir access for collecting geologic and sedimentation data. Dr. W. Nieckarz, University of Wisconsin-La Crosse, analyzed samples for cesium-137 and interpreted the results.

HISTORY

E. L. Norris and A. C. Stunts originally surveyed the area some time between June 1852 and September 1858. Topographic mapping had not been done before the construction of the first dam in 1907. The earliest map and drawing was done by John O. Forss in June 1919, a plan view of the dam and nearby area with a set of cross sections of the earth embankment. A planimetric map compiled in 1942 was superseded by a topographic map compiled from aerial photographs in 1965 by the U.S. Geological Survey. This map is the most recent map showing altitudes of the reservoir location.

The White River has been used continuously since the Chippewa Indians first came to the area about 1500. They and the white pioneers used the river as a source of food and for transportation. Logs were floated down the river in the late 1800's and early 1900's to a lumbermill about 20 mi downstream from the reservoir. The first use of the river for power generation was in 1855 when a small sawmill was built by T. P. Sibley and J. T. Welton at the site of the present powerhouse. It was run for approximately 2 years (Burnham, 1975). There also is a record of a rock-filled timber crib dam and papermill built at the same site in 1884 and later washed out.

An earth dike dam having a concrete spillway and four lift-type gates was built in 1907 at the site of the present dam by the White River Power Company of Ashland. The powerhouse was built 1,300 ft downstream at the site of the present powerhouse. A wooden penstock conveyed the water from the dam to the powerhouse. In 1909, the property was sold to the Ashland Light, Power, and Street Railway Company. This company later merged with others to form the Lake Superior District Power Company. In 1910, a flood destroyed the earthfill south of the concrete dam and destroyed the powerhouse. Both the dam and the powerhouse were rebuilt immediately.

A flood in 1926 severely damaged the dam on the White River. In 1927, the L. E. Meyers Company designed and built a completely new dam with two 25-ft-high tainter gates and new concrete spillway resting on the bedrock. A new wooden penstock and standpipe also were built. Except for the construction period around 1927 and occasional normal repairs, the dam, penstock, and powerhouse (pl. 1) were used almost continuously from 1907 until August 1974.

The reservoir was drained on August 19, 1974, to investigate a leak in one of the tainter gates, to check a crack in a concrete retaining wall, and to make minor repairs to the powerhouse. The repairs were expected to take about a week, but within hours after draining, a section of the wooden penstock collapsed. Because major repairs would have been necessary to resume power generation, the power company considered abandoning the generating facility and selling the dam and bridge to the State Highway Department. On November 26, 1974, they filed a petition with the FPC (Federal Power Commission) for abandonment of the facility, but withdrew it on May 2, 1975. On January 6, 1976, they filed a petition to repair and rehabilitate the dam, penstock, and generating facility. The FPC approved the petition on the recommendations from the Wisconsin Department of Natural Resources.

Construction began in the late summer of 1976, when the power company drained the reservoir. Construction included a new surge tank at the powerhouse and a 1,295-ft concrete pipeline connecting the dam and powerhouse. It also included excavating and backfilling the south earthen-dam wall, repairing the gates and concrete retaining walls, and rehabilitating the generators and turbines.

METHOD OF STUDY

FIELD METHODS

Surveying and test boring of the reservoir sediments began approximately 1 month after the reservoir was emptied. By that time, the sediments had dried and compacted enough to support vehicles. Fieldwork was aimed at obtaining sufficient data to determine particle size, weight, and volume of deposited sediments and total volume of the reservoir.

A series of range lines was laid out across the valley at approximately uniform intervals (pl. 1) to represent nine reaches of the reservoir. Test holes were augered at 75-ft intervals along each range line. Each hole was logged, and representative disturbed samples were collected for particle-size analyses at each distinct sediment layer.

Undisturbed samples also were collected from three pits at representative locations. The pits were excavated by a back hoe mounted on a tracked vehicle. A total of 15 undisturbed samples, weighing approximately 5 lb each, was collected from the exposed vertical sections. Before sampling, each section was examined and logged in detail.

Accurate horizontal and vertical control in the reservoir area was needed to calculate sediment volume. Alidade and plane-table surveys delineated the reservoir perimeter, located the range-end markers, and determined the topography of the sediment surface (fig. 2). Drill-hole locations and altitudes were surveyed, and surface altitudes along the range lines were mapped.

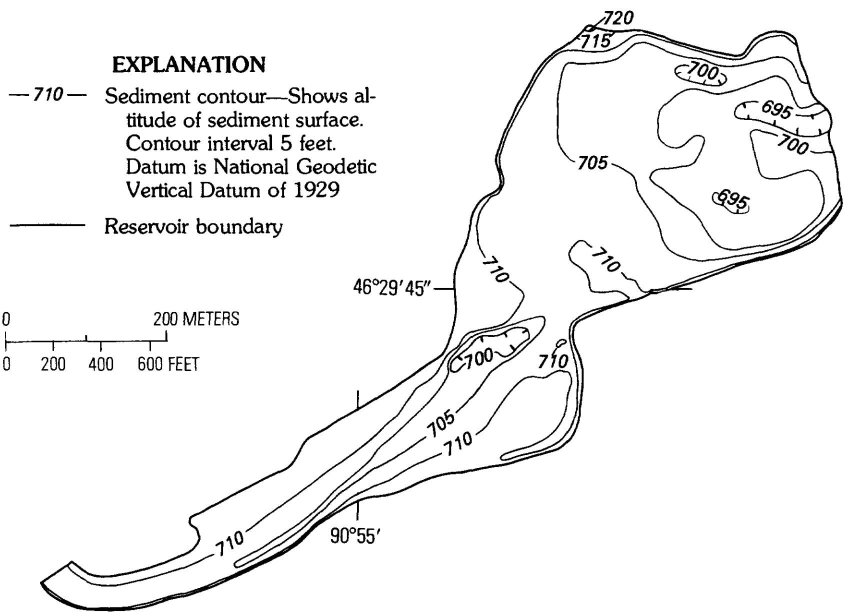

FIGURE 2.—Sediment-surface topography, September 1976.

RESERVOIR CAPACITY

Three methods of calculating the reservoir capacity were used and compared. The methods as described by H. G. Heinemann and V. I. Dvorak (1963, p. 845–856) are: (1) the average contour method; (2) modified prismoidal method; and (3) the stage-area-curve method. The stage-area-curve method and its application are described by H. G. Heinemann (1961). The stage-area-curve method uses the modified prismoidal calculations and is, therefore, a graphical representation of the modified-prismoidal method.

However, the stage-area curve also provides information on sediment distribution and on original capacity replaced by sediment.

STREAMFLOW, SEDIMENT, AND CHEMICAL-QUALITY MONITORING

White River streamflow, sediment discharge, and chemical-quality data were collected upstream and downstream from the reservoir. A stream-gaging station, White River near Ashland, 04027500, measuring daily streamflow has been in operation on the White River at the powerhouse since May 1948 (pl. 1). Flow at this site includes both that passing over the dam and, when power is being generated, that passing through the penstock. This station was upgraded from a nonrecording to a recording type in May 1976. A partial-record stream-gaging station, White River near Sanborn, 04027496, (not shown) was established on the White River 1.3 mi upstream from the reservoir pool. Streamflow was measured at this site every other day from May 1976 until September 31, 1976.

Samples were collected periodically for suspended-sediment concentration and particle-size analyses at the stream-gaging station downstream from the dam from November 1975 through September 1977. There was no power generated during this period, so streamflow at this site was entirely water that had passed over the dam. From May through October 1976, the station was operated as a daily suspended-sediment discharge station. At the upstream partial-record station, suspended-sediment concentration and discharge were measured every other day.

Eight samples of the White River were collected for chemical analyses. Four samples were collected at each of the two stream-gaging stations. Three sets of samples were collected while the reservoir was full and one set while it was empty.

RELATIONSHIP BETWEEN DRAINAGE-BASIN CHARACTERISTICS AND SEDIMENT YIELD

The White River and its tributaries upstream from the reservoir drain a 279-mi^2 area. Based on scant data, the average annual sediment yield for the whole drainage basin is estimated to be 50 tons/mi^2. However, 70 percent of the basin lies in the area having the lowest average annual sediment yield in the State (Hindall, 1976).

TOPOGRAPHY AND DRAINAGE

The drainage basin has two areas of sharply contrasting topography. The stream headwaters (the southwestern part of the basin) are within a glacial end moraine (Thwaites, 1956). This is a highland area, 1,200 to 1,400 ft above sea level, having a rolling or uneven and hummocky surface. This highland slopes sharply northeastward onto a relatively flat lowland sloping gently toward Lake Superior. In the drainage basin itself, this red-clay lowland slopes from about 1,000 ft at the base of the highland to about 800 ft above sea level. This lowland area is approximately delineated by the red-clay boundary in figure 1.

Because the red clay is so erodible and the White River so geologically young (less than 12,000 years old), the river is still rapidly cutting downward and dissecting the red-clay plain. This has resulted in several steep unvegetated streambanks more than 50 ft high.

SOILS, VEGETATION, AND LAND USE

Soil types are closely associated with the topography of the drainage basin. Coarse-textured, very permeable, sandy soils have developed on the thick sand and gravel in the moraine highland. Very fine-textured impermeable soils have developed on the red-clay plain. These soils are very poorly drained, especially in the many minor depressions. Soils along the steep slopes between the highland and the plain are intermediate-textured silt loams, but include patches of clayey soils.

Vegetation and land use are directly related to soil type and topography. The whole area was covered by forest, before logging in the late 1800's and early 1900's. The area had been logged by the early 1920's. All the highland and much of the plain was either reforested or allowed to revert to forest.

The coarse-textured soils and topography of the highland are not well suited for crop farming. More than half of it is forested, although much of it is used for cattle grazing. Crops have been confined to the gently rolling plain. Dairy farming has declined since World War II because of relatively poor drainage and low fertility of the red-clay soil and rising costs of fertilizers. The acreage in corn also has declined since the 1940's, but hay acreage increased. A land-use map (Northwest Regional Planning Commission, 1976) showed that less than 10 percent of the basin is agricultural or cleared land. Furthermore, much of this small area (less than 30 mi^2) is hay and other grass crops that significantly reduce erosion and sediment yield.

Most of the drainage area above the reservoir contributes little sediment to the streams. Heavy forests, coarse permeable soils, little farming, many lakes, and closed land-surface depressions combine to keep surface runoff and sediment yields low (less than 10 tons/mi ^{2}/yr). The drainage area covered by red-clay soils, particularly the steep unvegetated streambanks, contributes a disproportionately high share of the sediment. However, a longer period of more detailed data collection would be necessary to quantify this.

HYDROLOGY

STREAMFLOW CHARACTERISTICS

The White River is perennial and has a high base flow upstream from the stream-gaging station at the powerhouse. Streamflow has ranged from 3.1 ft ^{3}/s on April 28–30, 1949, to 6,270 ft ^{3}/s on July 1, 1953, while the average discharge for the 28-year period of record is 286 ft ^{3}/s. Low-flow characteristics of the river are important in the operation of a hydroelectric generating facility. Once every 2 years, on the average, the flow of the White River may reach a minimum of 148 ft ^{3}/s for 7 consecutive days and once every 10 years may reach a minimum of 126 ft ^{3}/s for 7 consecutive days.

Knowledge of high-flow characteristics is important to the operation of a storage reservoir and also to riparian property owners. The maximum discharges of the White River that can be expected on the average of once every 2 years and once every 50 years are 2,900 and 6,700 ft ^{3}/s, respectively.

SEDIMENT TRANSPORT

Sediment transport in the White River is typical of streams draining the red-clay area of northwestern Wisconsin. During periods of normal to low flow, the sediment concentration and discharges are generally low. The highest concentrations and greatest discharges occur when upland and channel erosion contribute large amounts of sediment to the streams. These periods are generally when storms or melting snow causes surface runoff.

Based on the period of sediment-data collection, concentrations of suspended sediment in the White River are generally less than 15 mg/L (milligrams per liter) during low to normal flow. Mean concentrations during higher flows (500 to 1,000 ft ^{3}/s) are approximately 90 mg/L at the gaging station at the powerhouse. The maximum-measured suspended concentration was 1,850 mg/L while the reservoir was being drained.

RESERVOIR EFFECT ON THE WHITE RIVER

The White River Reservoir affects downstream sediment concentrations by trapping the sediment entering from upstream.

This is illustrated by the low (90 mg/L) concentrations at the powerhouse gaging station during high flows (500 to 1,000 ft ^{3}/s). However, this figure is based on few high-flow measurements. During the early life of the reservoir, the trap efficiency was possibly as high as 80 percent. That is, the reservoir retained about 80 percent of the sediment that flowed into it. As the reservoir filled with sediment, its trap efficiency declined until today its trap efficiency is probably about 20 percent. As the reservoir lost its storage capacity through deposition, it also lost its ability to trap silt and clay. Trap efficiency for coarse sediment has probably remained high throughout the life of the reservoir.

Figure 3 shows sediment discharge both upstream (near Sanborn) and downstream (near Ashland) from the reservoir. The discharges at both sites were approximately equal before and after repair.

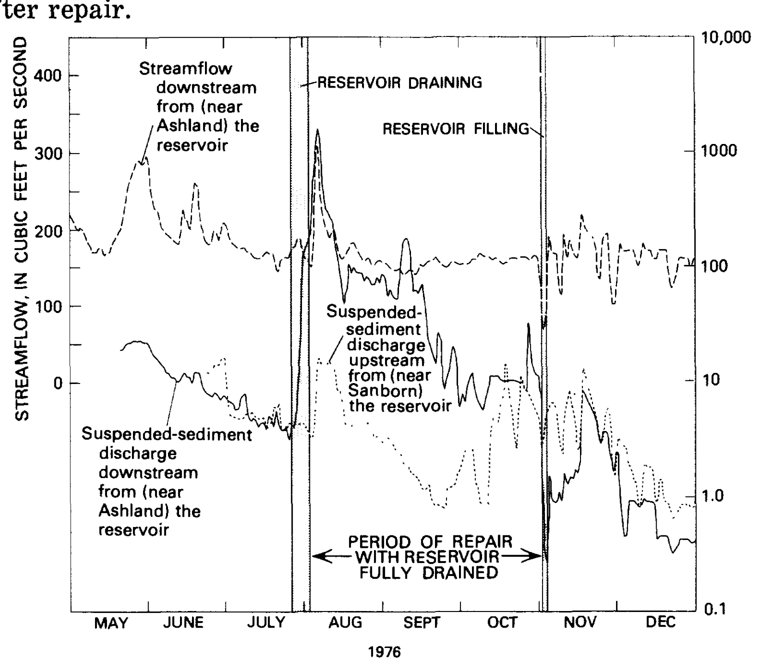

FIGURE 3.—Streamflow and suspended-sediment discharge in the White River.

The draining of the reservoir drastically increased the sediment loads passing the downstream sampling site. Loads passing the upstream site continued to decrease throughout the dry summer and fall (fig. 3), except for a temporary increase caused by a rainstorm in early August. Sediment loads at the downstream site increased soon after the gates were opened, and remained high throughout the July to November construction period. This increase was not immediate, but began only when reservoir sediments were exposed. The largest increase occurred when the river actually began downcutting into the exposed reservoir bed.

Effects of runoff from the rainstorm in early August are clearly evident on the hydrograph of figure 3. It was during this storm that both the maximum concentration and daily load occurred. Even though the loads and concentrations declined steadily during the construction period (August 6 to November 1, 1976), they remained above normal due to continued downcutting through the exposed sediment. About 7.5 acre-ft of sediment was washed out of the reservoir during this period. After the gates of the dam were closed on November 2, 1976, and the reservoir level reached permanent pool elevation, the downstream sediment loads returned to preconstruction levels.

Draining the reservoir affected the size of suspended material transported by the White River. Samples collected at the downstream gaging station with the reservoir being full indicated that about 80 percent of the suspended sediment was finer than 0.062 mm. Only about 50 percent of the suspended material was finer than 0.062 mm when the reservoir gates were open. Scant data for size of suspended material transported past the upstream site also indicated that about 80 percent of the incoming suspended sediment was finer than 0.062 mm.

CHEMICAL QUALITY

The White River near the reservoir is a calcium bicarbonate type water with moderate hardness. Hardness ranges from 84 to 92 mg/L, while having a median value of 88 mg/L. Dissolved-solids concentrations are low, generally less than 121 mg/L. Data are insufficient to show what effect the reservoir has on the chemical water quality. Samples collected upstream and downstream from the pool during the study had almost identical concentrations (table 1).

A water-quality sample also was taken of water seeping from the bank where the river had cut down through the reservoir sediment. The analysis is compared with those of the White River in table 1. This seep represents interstitial water. Its high mineralization results from large amounts of soluble salts derived from the clays and organics in the sediment. This heavy mineralization is further aided by long contact with the sediment.

TABLE 1.—*Water quality in the White River Reservoir*

[Chemical analyses in milligrams per liter except iron and manganese which are in micrograms per liter. Analyses by U.S. Geological Survey]

	White River (reservoir full)						White River (reservoir empty)		Seep from sediment
Date of collection	June 7, 1976		July 20, 1976		August 9, 1977		October 5, 1976		September 21, 1976
CST (Time of collection)	1615	1430	1615	1445	1400	1200	1445	1300	1100
Sampling location	Upstream from reservoir	Downstream from reservoir	Upstream from reservoir	Downstream from reservoir	Upstream from reservoir	Downstream from reservoir	Upstream from reservoir	Downstream from reservoir	In reservoir
Discharge (ft^3/s)	181	188	162	164	151	--	165	158	--
Specific conductance (micromhos)	175.0	175.0	190.0	190.0	180.0	180.0	235.0	230.0	1,420.0
pH (units)	8.5	8.2	8.3	8.2	8.0	7.8	8.6	8.5	7.0
Water temperature °C	24.0	23.5	24.0	22.0	18.5	20.0	11.0	10.0	13.0
Total hardness as $CaCO_3$	90.0	89.0	87.0	84.0	88.0	87.0	92.0	89.0	750.0
Dissolved calcium (Ca)	25.0	24.0	24.0	23.0	24.0	24.0	24.0	24.0	220.0
Dissolved magnesium (Mg)	6.8	7.0	6.5	6.4	6.7	6.6	7.7	7.0	48.0
Dissolved sodium (Na)	2.9	2.9	3.0	2.9	3.0	3.0	2.7	2.8	4.9
Dissolved potassium (K)	.9	.9	.8	.8	1.1	1.1	.9	.9	5.9
Bicarbonate (HCO_3)	108.0	108.0	106.0	106.0	100.0	100.0	143.0	109.0	935.0
Carbonate (CO_3)	.0	.0	.0	.0	.0	.0	.0	.0	.0
Alkalinity as $CaCO_3$	89.0	89.0	87.0	87.0	82.0	82.0	117.0	89.0	767.0
Dissolved sulfate (CO_4)	2.6	2.4	7.7	7.7	2.8	2.8	1.3	7.3	4.6
Dissolved chloride (Cl)	.6	.8	.5	.6	1.1	1.3	2.0	2.6	3.1
Dissolved fluoride (F)	.1	.1	.1	.1	.0	.0	.1	.1	.1
Dissolved silica (SiO_2)	11.0	10.0	12.0	12.0	12.0	12.0	14.0	14.0	29.0
Dissolved solids (residue at 180°C)	108.0	111.0	110.0	106.0	107.0	108.0	121.0	112.0	986.0
Nitrogen, total as N	.25	.33	.19	.56	.15	.39	.11	.11	13.0
Phosphorus, total as P	.03	.05	.03	.03	.02	.04	.04	.04	1.6
Total organic carbon (C)	3.0	2.9	--	--	4.2	6.0	--	--	16.0
Dissolved iron (Fe)	30.0	20.0	--	--	40.0	40.0	--	--	58,000.0
Dissolved manganese (Mn)	10.0	10.0	--	--	10.0	20.0	--	--	--
Carbon dioxide (CO_2)	.5	1.1	.09	1.1	--	--	.6	.6	--
Phytoplankton, total cells per milliliter	1,900.0	2,600.0	1,200.0	1,400.0	--	--	2,000.0	840.0	--
Suspended-sediment concentration	9.0	38.0	19.0	17.0	--	--	6.0	31.0	--
Suspended-sediment particle size (percent finer than 0.062 mm)	--	95.0	--	87.0	--	--	--	46.0	--

INFLUENCE OF PRERESERVOIR TOPOGRAPHY ON SEDIMENT DEPOSITION

The prereservoir-valley topography was similar to the topography upstream and downstream from the reservoir today. Steeply sloping valley walls extended along both sides of the reservoir. The valley was narrow along the upstream reach of the reservoir. The south shore through this reach (pl. 1) is a steep wall of Freda Sandstone of Precambrian age (Thwaites, 1912, p. 55). Near the middle of the reservoir the river meandered to the north, deflected by a point of land that is the most conspicuous promontory along the reservoir perimeter. Range-line end marker no. 8 is located on this point (pl. 1). The prereservoir valley widened downstream from this location. The river meandered across this wide downstream reach, leaving the reservoir area just south of the present concrete dam. Much of the valley floor in the present pool area was wooded, as indicated by many stumps sticking up above the sediment. The contour map of the prereservoir surface shows the configuration of the valley within the reservoir perimeter and the trace of the old river channel (fig. 4).

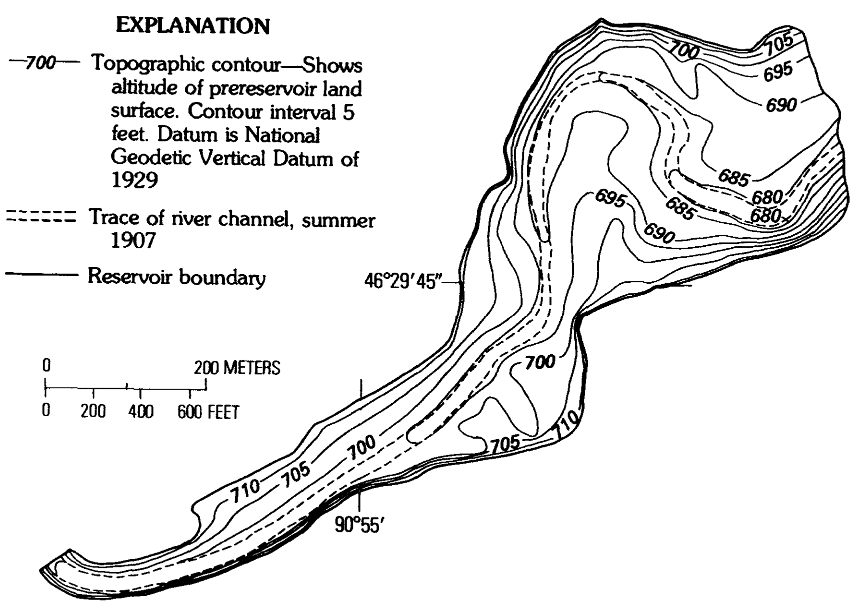

Figure 4.—Prereservoir-surface topography, summer 1907.

The shape of the valley influenced the distribution of sediment in the reservoir. It controlled the development and location of coarse-grained deposits in the upstream end of the reservoir. The right-angle bend in the White River, as it enters the reservoir, is geologically controlled by a vertical exposure of Freda Sandstone along the southern shore. Stream velocities remain relatively high for approximately 1,200 ft along this shore. Much of the sediment along the southern shore of this reach is coarse gravel and boulders derived from mass wasting along the outcrop. On the north side of this reach, a large amount of sand was deposited early in the life of the reservoir, forming a point bar along the inside of the stream meander. (A point bar is a sand or gravel bar that develops parallel to streamflow along the inside of a stream meander as the stream channel migrates toward the outer bank.) The streamflow directed most of its erosive energy against the exposed sandstone on the southern shore while this point bar developed along the northern shore downstream from the bend. Sand deposition continued on the shore side of this bar until a narrow, quiet-water trough developed between the bar and the northern shore. After sediment filled in the area north of the bar to pool elevation, marsh vegetation became established and this contributed to more sediment deposition, especially during high flow. This has reduced the size of the original pool area. At present, this point bar is a swampy area containing a small, shallow 1- to 2-ft deep backwater pond along the north edge of the reservoir.

Sediment also has accumulated in a cove along the southern shore of the reservoir. The upstream "head" of this cove is formed by the Freda Sandstone protruding north into the reservoir. The downstream end is the promontory on which range-line end marker no. 8 is located (pl. 1). The sandstone deflected flow slightly toward the north side of the reservoir, allowing sediment to accumulate in the cove. As early as 1951, sediment had built up above pool elevation. This sediment has been covered with swamp grasses and small trees (pl. 1), further aiding in deposition during high water. The river cut into these deposits when the reservoir was drained, exposing some sloping foreset beds of sand. The exposures showed isolated pockets of steeply dipping bedded sand lying on the prereservoir surface.

A ridge of sediment also has been built up near pool elevation north from the promontory where range-line end marker no. 8 is located. This ridge extends out from this point for several hundred feet and acts as a breakwater diverting flow north into the pool area. It also marks the downstream extent of the more dynamic sedimentation activity in the reservoir.

Bottom-set beds are confined to the pool area downstream from this point to the dam and along the north edge of this wide area. They are flat-lying silts, but include clay and fine sands that have filled the prereservoir valley.

On the north edge of the pool area, approximately 900 ft from the dam, a delta has formed at the foot of a large gulley (pl. 1). This delta is now covered by marsh vegetation. Construction work in 1959 on Highway 118 changed the drainage pattern locally so that runoff moved south toward the reservoir, instead of north and east into the White River downstream from the reservoir. This runoff cut the gully while sediment was deposited as a delta into the reservoir. The delta now extends about 150 to 200 ft out from the original shoreline into the quiet-water pool area. The Soil Conservation Service, in 1974, stabilized the slopes of the gulley as part of a study to find effective erosion-control methods. Though not quantitatively measured in this study, a visual inspection showed that erosion has been significantly reduced.

RESERVOIR-SEDIMENT CHARACTERISTICS

THICKNESS

The thickness of the deposited sediment ranged from less than 1 ft along the reservoir shores to slightly more than 20 ft where it has filled the original stream channel in the lower reservoir pool area. Difference in the sediment thickness is due to the irregular prereservoir surface and flow pattern in the reservoir (figs. 5 and 6).

PARTICLE SIZE

Deposited sediment ranged in size from clay and silt in the downstream end of the reservoir to large cobbles and even boulders at the upstream end of the reservoir. Size composition of all samples (15 in–place samples and 260 samples collected from various depths in the drill holes) averaged 43 percent sand, 40 percent silt, and 17 percent clay. This excludes the cobbles, boulders, and gravel at the upstream end of the reservoir. Sand ranged from 5 to 99 percent in individual samples, silt from 1 to 76 percent, and clay from 0 to 49 percent.

The deposited sediment analyzed in the White River Reservoir was relatively coarse. This is partly because velocities through a

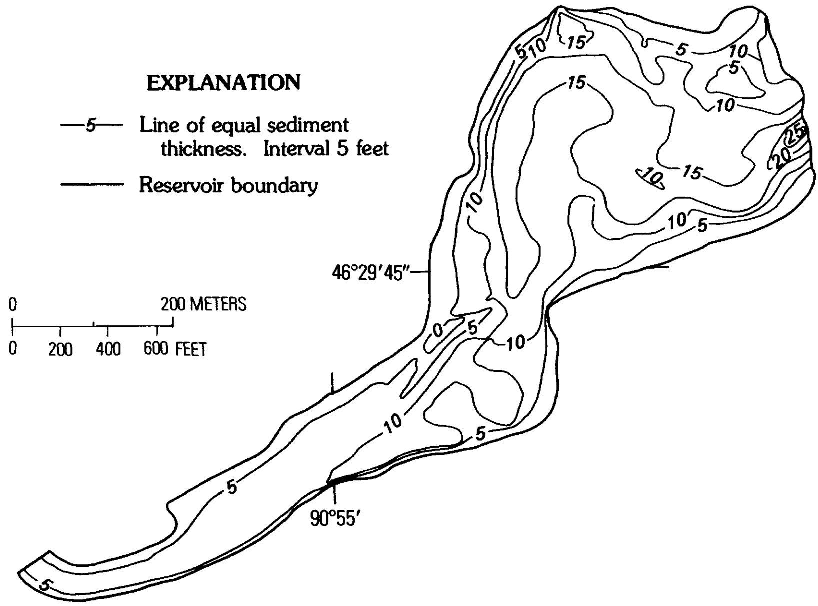

FIGURE 5.—Sediment thickness, September 1976.

small upland reservoir such as this one are too high to allow much settling of fine-grained sediments. This is particularly true during periods of high flow, when most sediment is being transported. Also, a considerable amount of clay and silt was washed out each time the reservoir was drained.

VERTICAL AND HORIZONTAL VARIATION

Abrupt vertical changes in the particle size of the sediments are common, indicating a shift in depositional environment with time. However, the general pattern of fine sediments in the downstream end of the reservoir grading to coarser deposits in the upstream end of the reservoir is apparent. Particle-size distribution curves (fig. 7) compare the types of sediment deposited in three areas of the reservoir. The curves represent the average of the entire thickness of deposited sediment from a representative drill hole in each area. The average sand, silt, and clay percentages for all holes along each range line, as well as the average for the range line, are plotted on a trilinear graph (fig. 8). This shows the trend of decreasing silt and clay toward the upstream end of the reservoir and a continuous increase in sand.

The depositional process was complex in the upstream end of the reservoir. Deposits north of the point on which range-line

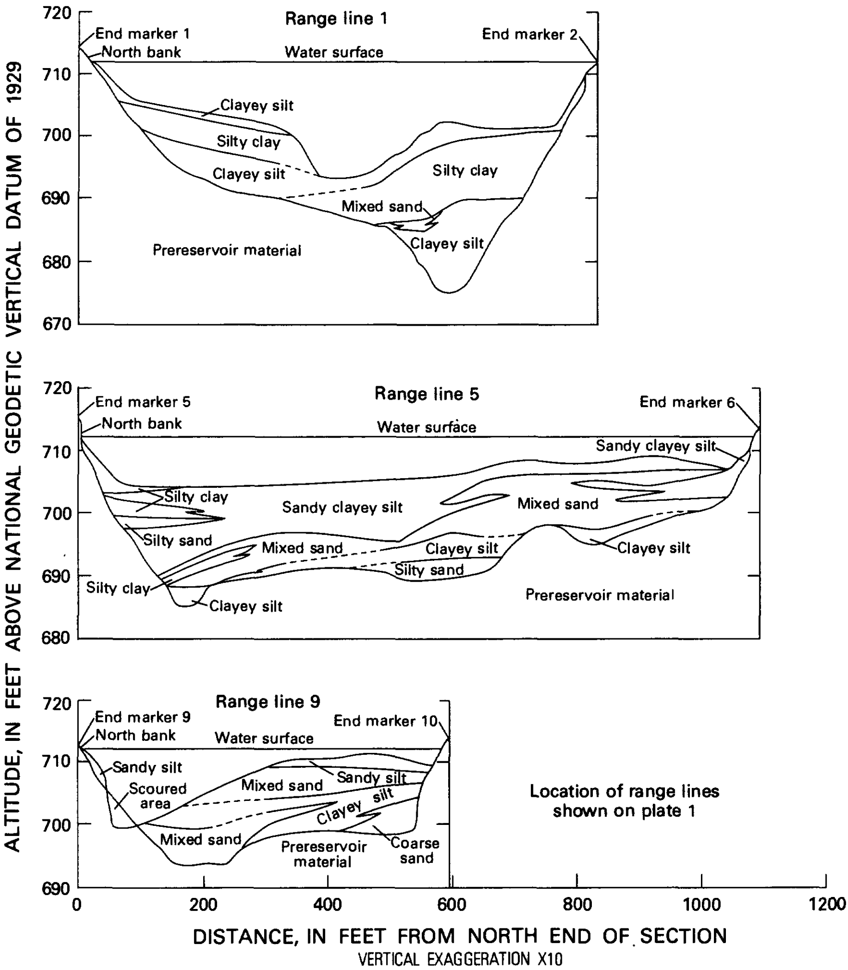

FIGURE 6.—Sediment sections along range lines 1, 5, and 9.

end marker no. 8 is located (pl. 1) and upstream from there has increased in the amount and size of sand. However, vertically alternating sand and silt layers reflect the flow shifting back and forth across the reservoir. Previous studies indicate that flow in a reservoir deposits coarser material along its path while holding silt and clay in suspension. A large portion of this fine material is carried by reverse eddy flow back to the upstream end of the pool and deposited there in pockets on the sediment surface (Vanoni, 1975, p. 593). This would explain the sand content of the sediment peaking along range line 7 and decreasing slightly upstream from that point, particularly along the southern edge of range line 9 (pl. 1).

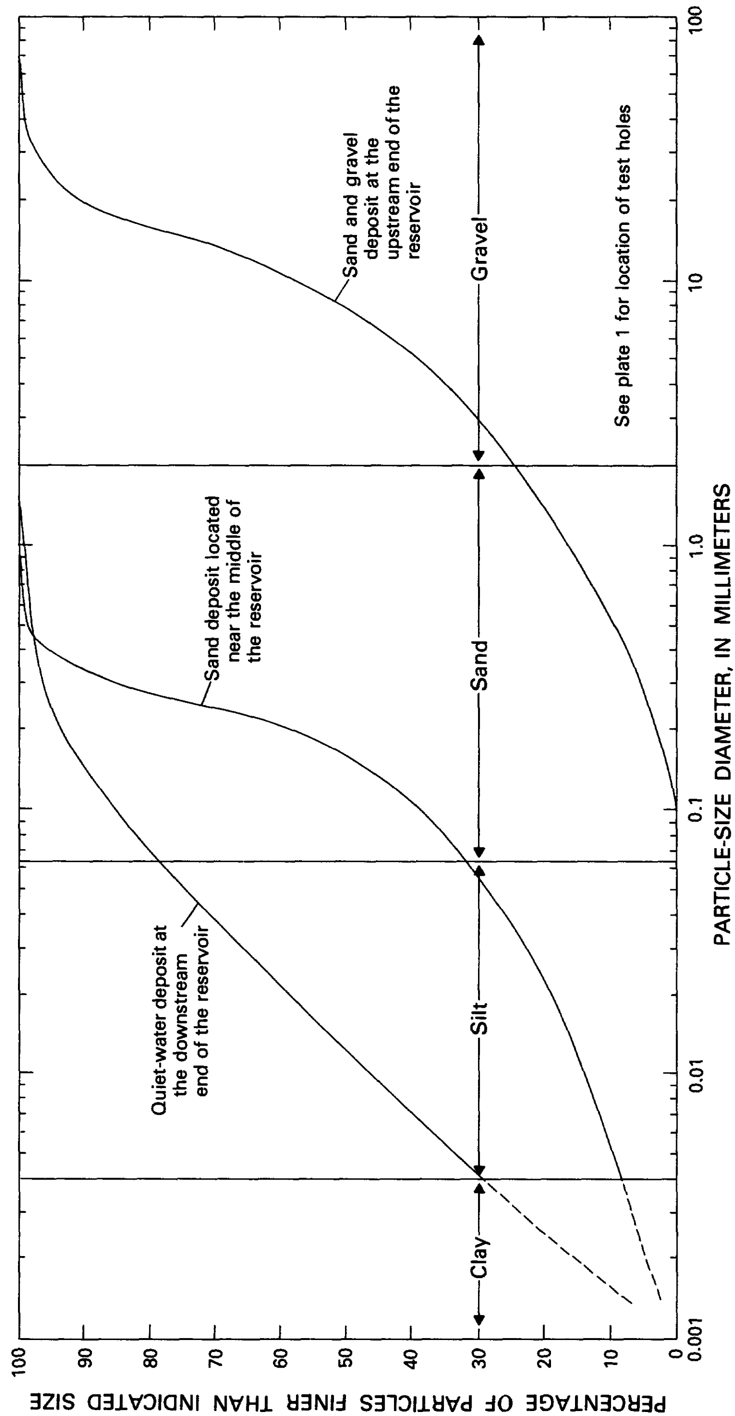

FIGURE 7.—Particle-size distribution for three types of sediment deposited in the reservoir.

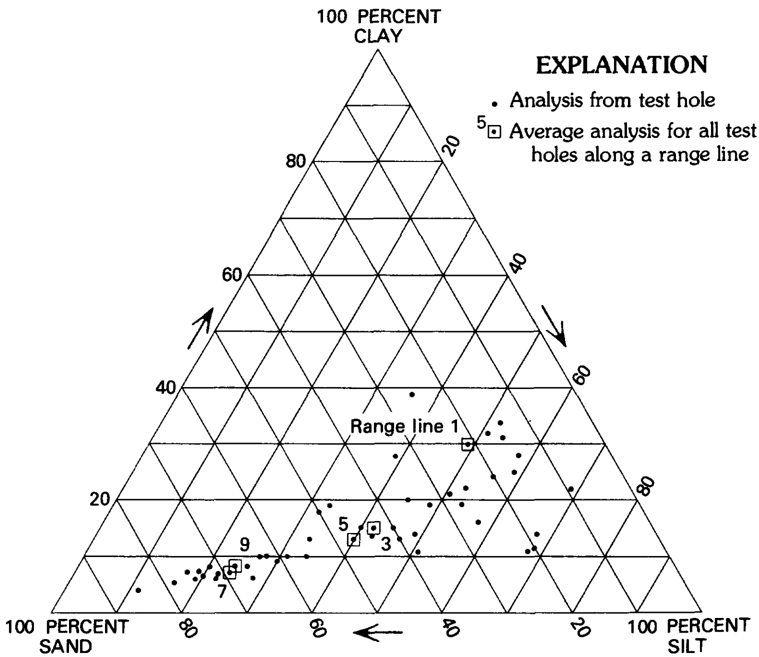

FIGURE 8.—Percentage of sand, silt, and clay throughout the reservoir. See plate 1 for location of test holes and range lines.

The northern half of range line 9 is in an area of scour (pl. 1). That is, the river eroded the sediment and cut into the prereservoir surface when the reservoir was emptied. It was impossible to determine how much sediment was present at this location before the reservoir was drained. A survey of the reservoir conducted in 1966 (Wisconsin Conservation Department, 1966) showed that the surficial sediment in this area was "muck," with its surface altitude as much as 10 ft higher than the altitude at the time of this study. The prereservoir surface and, therefore, the sediment deposited were estimated for this area.

Deposits upstream from range line 9 were the point bar deposits, extending along the north edge of the reservoir (pl. 1), and coarse gravels and boulders at the base of the outcropping Precambrian sandstone along the south edge. All of the boulders and most of the coarser gravels were derived from this outcrop. The finer gravels were of various lithologies and were more rounded, indicating a source upstream.

Organic material also was present in the deposits. This material ranged from whole tree trunks, 2 to 3 ft in diameter, washed in during high water, to small twigs, leaves, and fibrous plant roots.

Areal distribution was not uniform throughout the reservoir. Vertical distribution also was irregular, consisting of occasional 0.1- to 0.2-ft thick layers of black, partially decomposed leaves and twigs. A section along the bank, cut through the sediment between ranges 5 and 7 (pl. 1), showed several feet of thin (less than 0.1 ft) layers of partially decomposed leaves and twigs alternating with layers of silty sand.

SORTING AND SKEWNESS

Coefficients of sorting and geometrical skewness were determined for many individual samples. The coefficient of sorting is a measure of the spread of the particle-size range for a given sample: the wider the spread, the poorer the sorting. The coefficient of geometrical skewness indicates the degree of symmetry of the size distribution to the median for a particular sample (Twenhofel and Tyler, 1941). More than half the samples were well sorted, but more importantly, less than 10 percent were poorly sorted. This indicates that depositional conditions remained relatively constant while each sediment layer was being deposited. In more than 80 percent of the samples, the coefficient of skewness showed that maximum sorting took place in the particles coarser than the median for the sample. This indicates that in each layer, one or two coarse sizes predominated. The vertical variation in particle size in most test holes indicated that the depositional environment shifted throughout the reservoir from time to time. This is evidenced by distinct and abundant layering, especially in the upstream two-thirds of the reservoir. The depositional environment was less dynamic in the deeper downstream pool area. Thus, the sand layers that did occur in the clayey silt of the deeper pool area were thin and consisted of very fine to fine sand.

DENSITY

The 15 undisturbed samples taken from the 3 pits in the reservoir were analyzed for dry density and particle size using the hydrometer method. The densities, listed in table 2, ranged from 62.4 lb/ft^3 for a clayey silt in test pit number 1 to 93.6 lb/ft^3 for coarse to very coarse sand in test pit number 2. Prereservoir colluvial red clay from the interval 5.6 to 6.1 ft in test pit number 3 had a density of 89.3 lb/ft^3.

Lane and Koelzer (1943) established a relationship between sediment density and percent sand. This relationship is shown by the curve in figure 9. Data from the samples shown in table 2 also are plotted in figure 9. The two curves show close agreement.

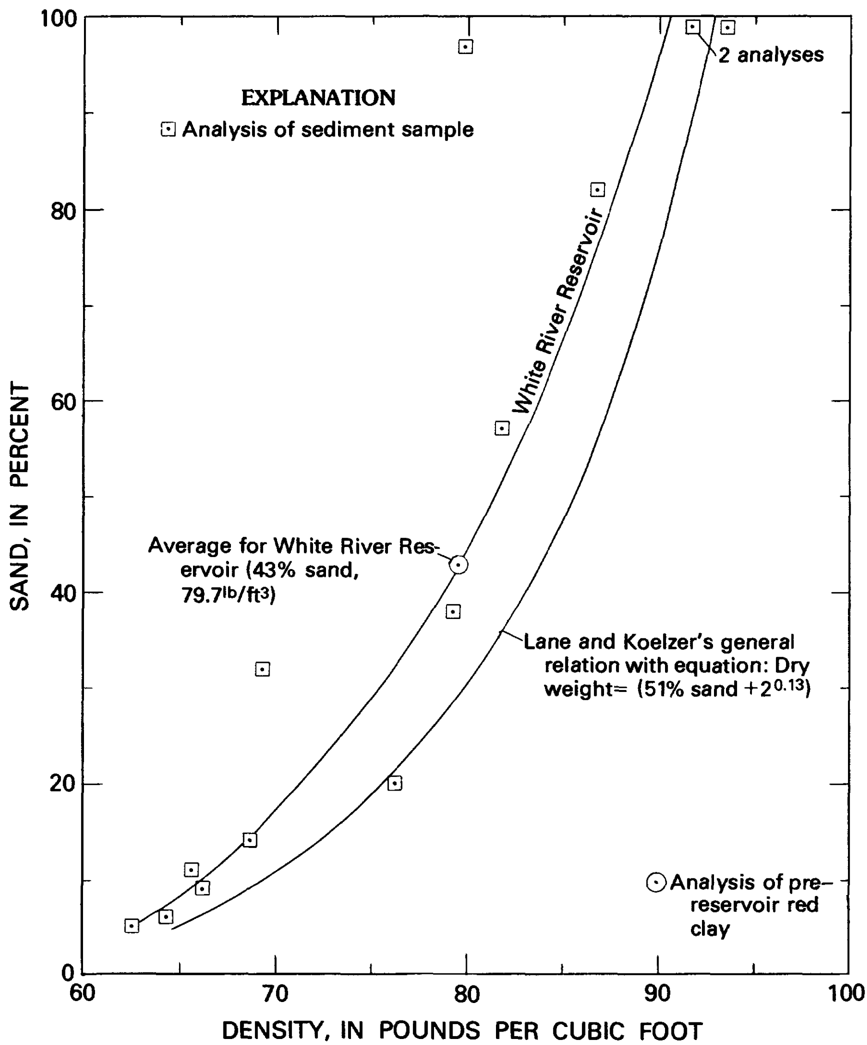

Figure 9.—Reservoir-sediment density compared to percent sand.

In addition to particle size, Lane and Koelzer accounted for the method of operating the reservoir and the sediment age, using the relation:

$$W = W_1 + K \log_{10} T$$

where: W equals the density, in pounds per cubic foot, of a deposit with an age of "T" years;

W_1 equals its initial density; and

K is a constant for each particle size (sand, silt, clay) that is dependent on reservoir operation.

TABLE 2.—*Density and particle-size percentages of undisturbed sediment samples*

Test pit No.	Sample depth (ft)	Physical description	Density (lb/ft^3)	Percent sand	Percent silt	Percent clay
1	1.3–1.8	Silt, clayey, gray-brown	62.4	5	83	12
1	3.2–3.7	Silt, clayey, gray-brown	66.2	9	77	14
1	4.0–4.5	Sand, very fine- to fine-grained, silty, light red-brown	81.8	57	35	8
1	5.0–5.5	Silt, clayey and medium- to very coarse-grained sand, dull red-brown	76.2	20	64	16
1	6.0–6.5	Sand, fine- to coarse-grained, dull red-brown	86.8	82	13	5
1	8.3–8.8	Silt, clayey, and very fine-grained sand, dark red-brown	79.3	38	50	12
1	10.5–11.0	Sand, medium- to very coarse-grained, light red-brown	91.8	99	1	0
2	1.0–1.5	Silt, clayey, sandy, dull red-brown	69.3	32	56	12
2	3.0–3.5	Sand, fine- to medium-grained, light red-brown; contains some organics	79.9	97	1	2
2	4.0–4.5	Silt, clayey, dull red-brown	68.7	14	73	13
2	8.8–9.3	Sand, coarse- to very coarse-grained, light red-brown	93.6	99	1	0
3	.5–1.0	Silt, clayey, dark red-brown; contains some light red-brown very fine sand layers	65.6	11	79	10
3	1.6–2.1	Sand, medium, light red-brown	91.8	99	1	0
3	3.0–3.5	Silt, clayey, dark red-brown	64.3	6	72	22
3	5.6–6.1	Clay, red-brown; contains some organics; prereservoir colluvium	89.3	8	70	22

W_1 and K values based on type of reservoir operation are shown for sand, silt, and clay in table 10 of Lane and Koelzer (1943, p. 49). As a "run-of-the-river" hydroelectric facility, the White River Reservoir has always been kept at or near its full capacity. Using the values for this type of reservoir operation from Lane and Koelzer's table, the calculated density of sediment in the reservoir was 80.3 lb/ft^3 assuming 43 percent sand, 40 percent silt, and 17 percent clay as the average particle size for the reservoir sediment, and 69 years of operation. The density values of 79.7 lb/ft^3 and 83.9 lb/ft^3 at 43 percent sand from the curves in figure 9 also compare closely with this calculated density.

Density and sand content of deposited sediment increased both with depth and with distance upstream from the dam. This areal variation in density is mapped in figure 10 using values based on the particle size-density relation shown in figure 9. The density change upstream from the dam also is shown graphically in figure 11. The points on the graph are averages for each range line at the sediment depths of 0 to 1 ft, 4 to 5 ft, and 9 to 10 ft. The slight decrease in density and particle size along range line 9 was probably due to back-eddy flow depositing silt and clay-sized sediment there. It should be noted that this increase in density with depth is due to a general increase in particle size and not due to the increase in compaction time

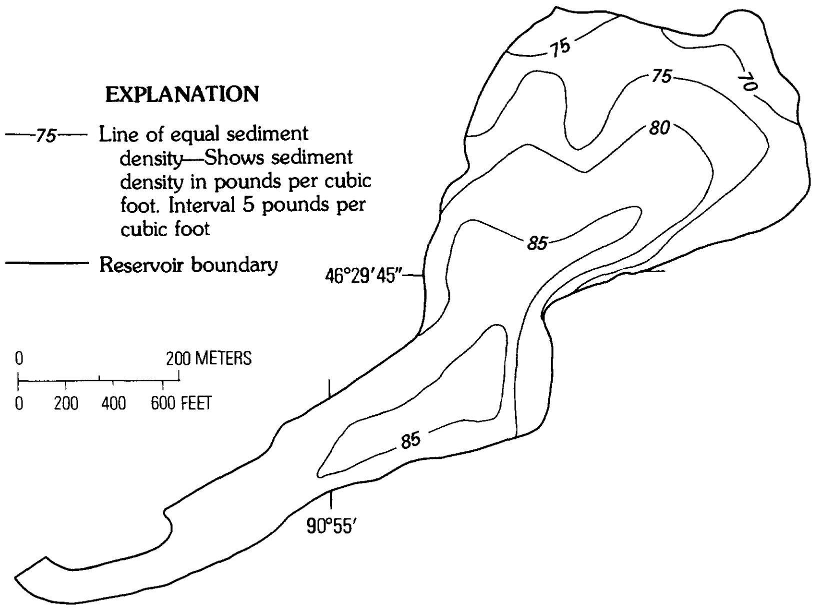

FIGURE 10.—Sediment density.

associated with depth. Approximately 8 to 10 ft of predominantly clayey silt located 50 ft upstream from range line 3 near the north shore (pl. 1) compacted less than 0.2 ft, 5 weeks after draining the reservoir.

RESERVOIR CAPACITY AND SEDIMENT VOLUME

The original capacity of the White River Reservoir in 1907, the remaining capacity, and the volume of deposited sediment as of September 1976 are shown in table 3. It also shows that the "Average Contour Method" and the "Modified Prismoidal Method" of computation give almost identical results. The original capacity was approximately 815 acre-ft in the summer of 1907. About 487 acre-ft of sediment had been deposited by September 1976, leaving 328 acre-ft of remaining capacity. The original 1907 surface area planimetered for use in this study is the pool area bounded by the dam and by a line extending across the valley approximately 100 ft upstream from range line 17 (pl. 1).

Using the average sediment density of 79.7 lb/ft^3 from figure 9, the total weight of sediment deposited through September 1976 was approximately 845,350 tons or a gross rate of about 12,250 tons/yr.

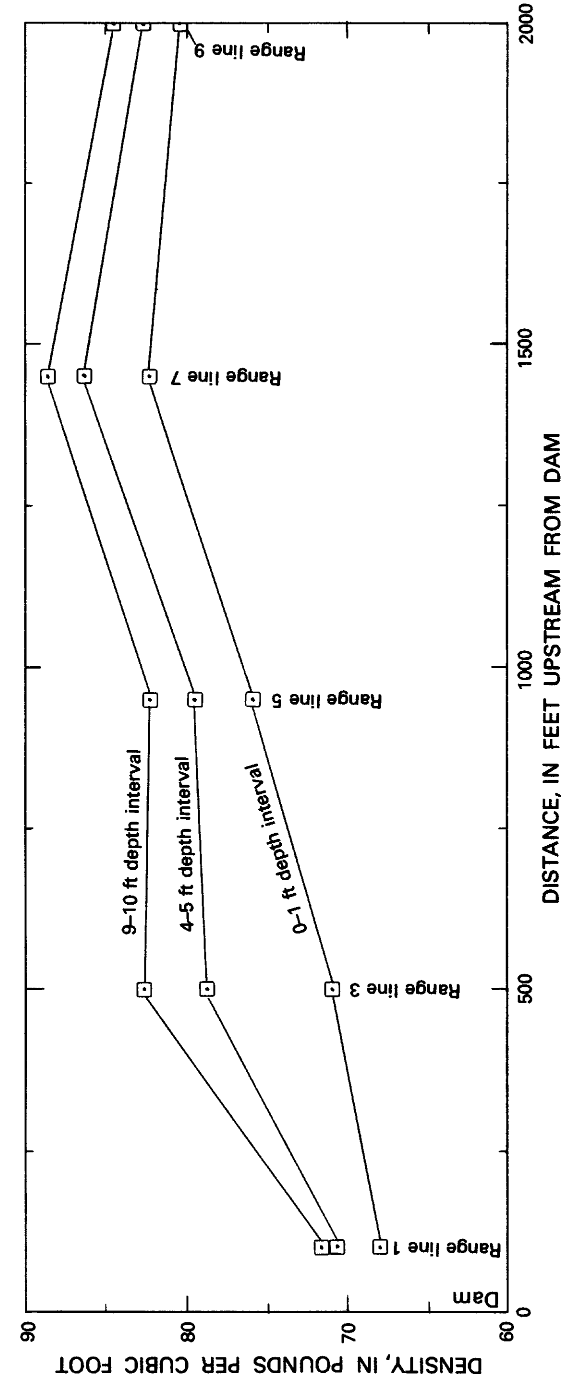

FIGURE 11.—Sediment density compared to distance upstream from dam.

TABLE 3.—*Reservoir capacity and volume of deposited sediment*

Method of computation	Original reservoir surface area (acres)	Original reservoir maximum depth (ft)	Original reservoir capacity, summer 1907 (acre-ft)	Remaining reservoir capacity, September 1976 (acre-ft)	Total volume of sediment deposited through September 1976 (acre-ft)
Average contour____	50.5	36	815	329	486
Modified prismoidal _	50.5	36	814	327	487

Just as important as the amount of sediment is the way in which it is distributed in the reservoir. H. G. Heinemann (1961) developed a set of three graphs showing the distribution of sediment in small Missouri River basin reservoirs, as part of a procedure to plan and design flood-retarding reservoirs in that area. The curves were prepared using original reservoir depth, capacity, and sediment volume. A set of these curves for the White River Reservoir is shown in figure 12. The three curves are:

1. Original capacity in 1907;
2. Distribution of sediment deposited before September 1976;
3. Original capacity replaced by sediment before September 1976.

The original capacity curve shows, for example, that only 16.5 percent or about 135 acre-ft of the original capacity was located in the bottom 50 percent or 18 ft of the total original reservoir depth but that 50 percent of the original capacity or about 407.5 acre-ft was located in the top 25 percent or 9 ft of the total depth.

The sediment-distribution curve shows the location of the sediment deposited as of September 1976. It shows that 50 percent of the sediment is deposited in the lower 63.4 percent or 23 ft of original depth. It also shows that 19 percent of the total sediment or about 155 acre-ft has been deposited in the top 7.2 ft (20 percent) of original depth.

The curve representing original capacity replaced by sediment shows the percentage of storage depleted up to a given elevation. In the White River Reservoir, all original capacity has been filled by sediment in the lower 44.4 percent or 16 ft of original depth. Also, 50.2 percent of the original pool area was less than 6 ft deep in September 1976 (fig. 2). Finally, the original capacity replaced by sediment curve shows that 59.8 percent of the total original capacity of the White River Reservoir has been replaced by sediment as of September 1976. This represents a 0.87 percent per year loss of storage capacity.

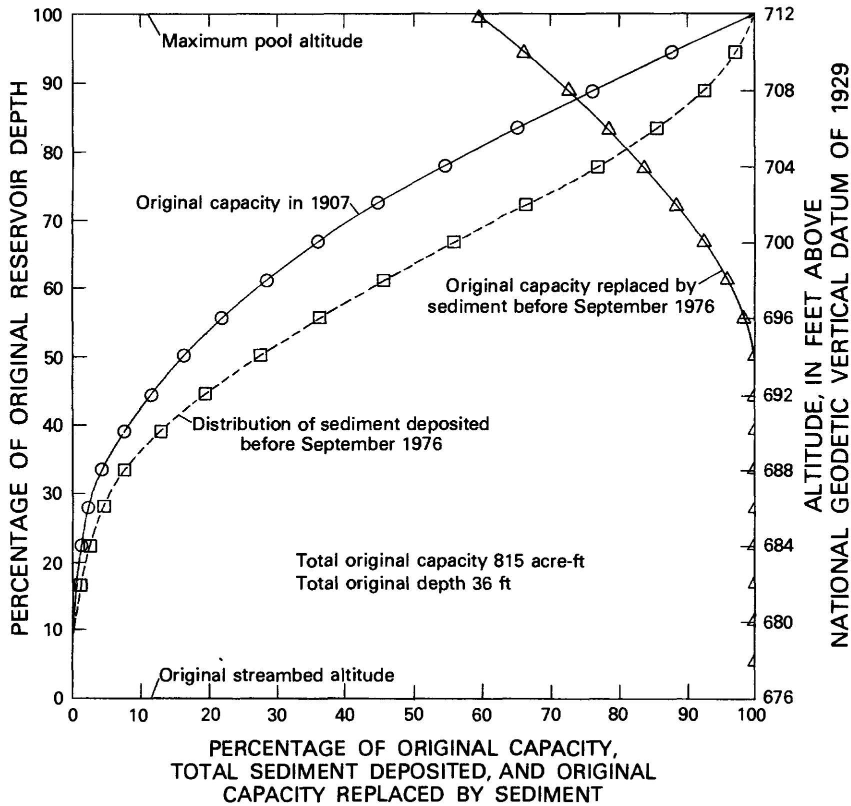

FIGURE 12.—Reservoir capacity and sediment distribution related to reservoir depth.

RATES OF SEDIMENT DEPOSITION

An attempt was made to determine the rate of deposition over the entire 69-year period. The rate of deposition for 1959–76 was determined by using a cesium-137 radioactive-tracer technique developed by Ritchie and McHenry (1973) at the U.S. Department of Agriculture Sedimentation Laboratory in Oxford, Miss. Cesium-137 is a radioactive-fallout product from atmospheric nuclear testing. It is strongly adsorbed by clay-sized soil particles. Differing concentrations of this radioisotope occur in soils and reservoir sediment deposited since 1959. Particularly high concentrations follow the periods of maximum atmospheric testing of nuclear weapons in 1959–60, 1963–64, and a small increase in concentration also is detectable following a minimum in 1967.

Three undisturbed Shelby-tube cores, approximately 600 mm long, were collected for cesium-137 analysis (pl. 1). Each core was cut into 20-mm increments. A gamma-ray spectrometric analysis was run on each 20-mm increment using a germanium-lithium detector to determine the relative concentration of cesium-137 in each increment. The cousts observed in the 0.662-MeV photopeak from the decay of cesium-137 are plotted as a function of depth in figure 13. In core 1–2, cesium-137 was

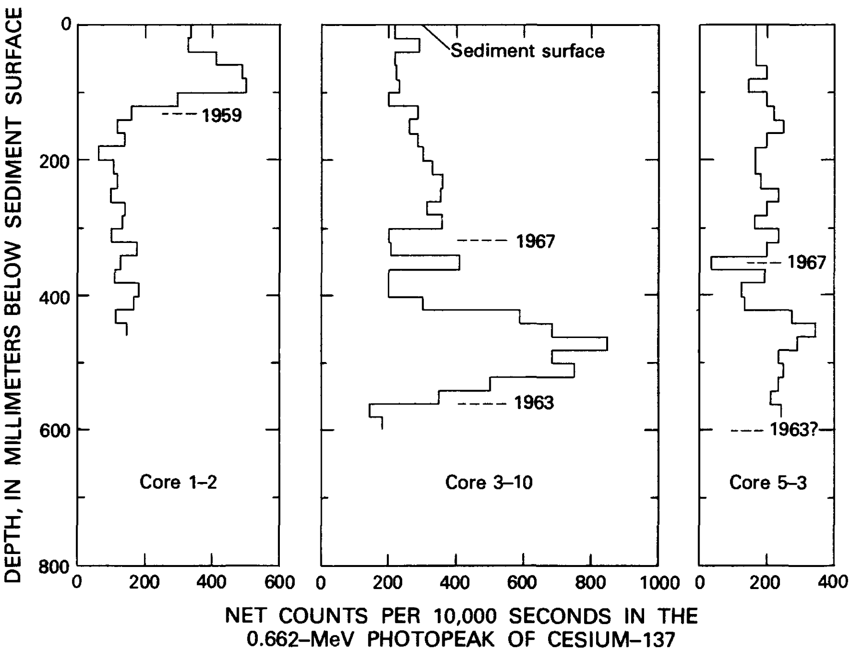

FIGURE 13.—Concentration of cesium-137 below the reservoir sediment surface.

present only in the upper 120 mm of sediment. Core 1–2 was taken along the north edge of range line 1 (pl. 1) in a location where sediment probably accumulated to near pool elevation early in the reservoir history so that wave action prevented further accumulation.

The contribution to the cesium-137 photopeak from the Compton scattering of other gamma-emitting radionuclides in all the samples was estimated to be 190 counts/10,000 seconds. Because visual examination of the total 1,024-channel gamma spectrum did not show any cesium peak in samples taken below 120 mm in core 12, it was assumed that no cesium-137 was present below this depth. Thus, it is probable that only 120 mm of sediment has been deposited in this location since 1959. This is an average annual rate of 7 mm/yr.

Analyses of the remaining two cores showed entirely different conditions of recent reservoir deposition. Core 3–10 was taken in a deep quiet-water area near the south end of range line 3 (pl. 1). A maximum cesium-137 activity associated with the sedimentation period just after 1963 and a low activity (no visible cesium-137 photopeak) associated with 1967 are both fairly well defined. The characteristic photopeak of cesium-137 was not present in samples taken below a depth of 560 mm. Therefore, it was assumed that the observed activity at 580 mm and 600 mm (less than 190 counts/10,000 seconds) was due to other radioactive sources. This indicates a sedimentation rate of 60 mm/yr from 1963–67, 36 mm/yr from 1967–76 and an average of 43 mm/yr from 1963–76 in this location.

Analysis of core 5–3 shows similar sedimentation rates, although the relative concentration of cesium-137 in the samples was somewhat less. It also appeared that the core did not entirely penetrate the post-1963 sediment because cesium-137 was observed in the last sample counted. The similarities between core 3–10 and 5–3 indicate that the cesium-137 activity should have ended 20 to 40 mm below this coring. Rates for core 5–3 are 65 mm/yr from 1963–67 and 38 mm/yr from 1967–76, and an average of 46 mm/yr from 1963–76 for this location.

The amount of sediment deposited during 1963–76 was calculated to be 74.3 acre-ft using the rates determined by the cesium-137 technique. This represented a 5.7 acre-ft/yr average rate of sedimentation during this period. Sediment deposition totaled 412.7 acre-ft during 1907–63, or 7.4 acre-ft of sediment annually. Part of this decrease in the sedimentation rate can be attributed to the greater trap efficiency earlier in the life of the reservoir. Also, the White River Reservoir was constructed shortly after logging had been completed in the area. This, along with a somewhat greater intensity of agriculture and poorer erosion-control practices of the time, contributed to heavier sediment loads earlier in the reservoir history.

SUMMARY AND CONCLUSIONS

Rates of sediment deposition in the White River Reservoir have changed significantly since the White River was permanently dammed in 1907. The average annual amount of sediment deposition over the entire reservoir history was 7.0 acre-ft/yr, whereas the rates of deposition during 1907–63 and 1963–76 were calculated to be 7.4 and 5.7 acre-ft/yr, respectively. The higher deposition rate early in the reservoir's history was due to greater trap efficiency and poorer erosion-control practices during the early 1900's.

The measured sediment inflow to the reservoir during the project was about 8 acre-ft/yr. This volume compares reasonably well with the computed rates of deposition, when reservoir trap efficiency is considered. Trap efficiency of the reservoir has declined from about 80 percent when the reservoir was new to about 20 percent at the present time. About 80 percent of the material leaving the reservoir is finer than 0.062 mm (in the clay-silt range). Sediment loads in the White River passing from the reservoir increased drastically during the period of dam and powerhouse repair and rehabilitation because the river picked up sediment as it eroded a deep channel through the deposited reservoir sediments.

Data are insufficient to show what effect the reservoir has had on the chemical quality of the river. Chemical analyses of samples collected both upstream and downstream from the pool limits give almost identical results.

Composition of deposited sediment ranged from clay and silt-sized particles in the downstream end of the reservoir to large cobbles and even boulders at the upstream end of the reservoir. Composition for all samples (275) averaged 43 percent sand, 40 percent silt, and 17 percent clay. This excludes the cobbles, boulders, and gravel at the upstream end of the reservoir. The calculated density of sediment in the reservoir was 79.7 lb/ft^3. Sediment density and sand content increased both with depth and with distance upstream from the dam.

The original capacity of the reservoir was approximately 815 acre-ft in the summer of 1907. About 487 acre-ft of sediment had been deposited in the reservoir by the summer of 1976, leaving 328 acre-ft of remaining capacity.

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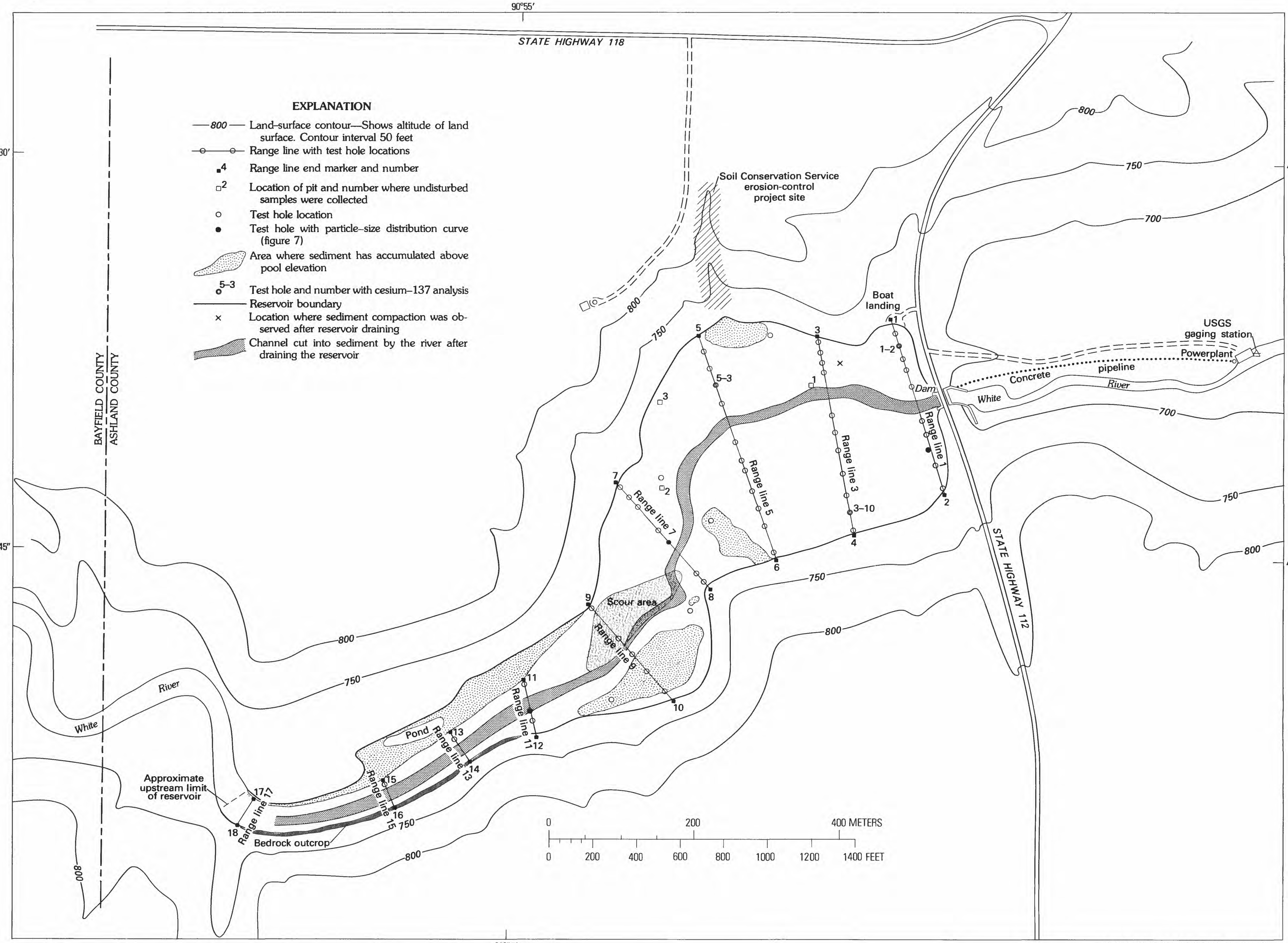

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INTERIOR—GEOLOGICAL SURVEY, RESTON, VA.—1979—W79736

GEOGRAPHY AND LOCATION OF RANGE LINES AND DATA SITES IN THE WHITE RIVER RESERVOIR AREA, NORTHWESTERN WISCONSIN